# BELLCOMM, INC.
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SUBJECT: Center of Gravity Motion and Initial SPS Motor Thrust Mistrim Effects on LOI and TEI Maneuvers - Case 310

DATE: October 15, 1968

FROM: F. La Piana

## ABSTRACT

Using computer program simulations of the command module guidance system, digital autopilot and spacecraft rigid body rotational dynamics, evaluations of C.G. motion and initial thrust mistrim effects on single burn LOI and TEI maneuvers were made. Preliminary lunar landing trajectory and vehicle parameters were used with the SUNDISK/COLOSSUS autopilot.

The digital autopilot simulation includes the start-up delay, the 4-second interval before steering signal acceptance and the use of a time-to-go algorithm for steering termination. In addition, unity autopilot/dynamics simulations of both maneuvers were made and used as the reference (ideal) case.

Center of gravity motion (due to propellant consumption) produces thrust - C.G. misalignment and subsequent transient cross-axis error velocity maximum of 3.8 fps for LOI and 3.5 fps for TEI. When $3\sigma$ initial SPS thrust mistrim is added, the values become 10 fps for LOI and 11 fps for TEI. In all cases, the Guidance and Control system smoothly and completely eliminated the error velocities by the end of the burn and from a cross-axis error velocity viewpoint is a completely satisfactory system for LOI and TEI.

MEMORANDUM FOR FILE


1.  INTRODUCTION

The purpose of this study was to evaluate the effects of center of gravity motion (due to propellant consumption) and initial SPS motor thrust mistrim on single burn Lunar Orbit Insertion (LOI) and the Transearth Injection (TEI) maneuvers.  The figure of merit used is the deviation in vehicle cross-axis velocity from that obtained by unity (ideal) autopilot and vehicle dynamics simulation.

For this study, the command module guidance system, digital autopilot (DAP) and rigid body rotational dynamics simulations in the Bellcomm Powered Flight Performance Simulator computer program were used.  Vehicle parameters and preliminary reference trajectory data were taken from References 2, 3, 5 and 7.

2.  SIMULATION METHODS AND ASSUMPTIONS

a.  Guidance System

For the LOI into a 100 nautical mile orbit, and for the TEI maneuver, the velocity to be gained ($\overline{VG}$) equation used is:

$$\overline{VG} = \overline{VR} - \overline{V} \qquad \text{Eq. 1}$$

where $\overline{VR}$ is the velocity required and $\overline{V}$ is the "on-board" measurement of vehicle velocity.  The equation is solved every guidance cycle by the Command Module Computer.  The target vector data used in solving for $\overline{VR}$ was taken from Reference 2. The simulation LOI and TEI burn times and burn out position/velocity data very closely match those in the preliminary reference trajectory documents.

The familiar cross product steering equation:

$$\overline{W}_c = K \frac{\overline{VG} \times [C(\dot{\overline{VR}}-\overline{g})-\overline{a}_t]}{|\overline{VG}| \ |C(\dot{\overline{VR}}-\overline{g})-\overline{a}_t|} \qquad \text{Eq. 2}$$

was used for the simulations.  Values of C=1 and K=.075 were used for LOI, C=.5 and K=.1 were used for TEI.

b.  Digital Autopilot (DAP)

The DAP simulation used is that in the SUNDISK GSOP and includes all significant effects; the start-up delay of .675 seconds, the 4-second interval before steering command acceptance, and the rejection of new steering signals when the time-to-go (TGO) is less than 4 seconds are included.  TGO was computed using the algorithm implemented in the CM computer, (References 5 and 8), and is given in the Appendix.

For the LOI maneuver, using the CSM/LM vehicle, the seventh order digital filter was used.  For TEI, with the CSM vehicle, the first order filter was simulated in the DAP loop. DAP cycle time of 40 milliseconds was used except after "switch" (at 6 seconds) for the CSM/LM configuration when the filter gain was quartered and the cycle time changed to 80 milliseconds.

A "Unity Autopilot" simulation of both maneuvers was made.  For these cases, the commanded pitch-yaw rotation rates are assumed to be instantly achieved.  This simulates a unity gain inertialess ideal system which was used for guidance performance comparison with the actual DAP and vehicle dynamics simulations.

c.  Vehicle Parameters

The basic thrust and mass parameters were taken from Reference 2.  Mass at LOI start was 2786.96 slugs, at TEI start 1024.40 slugs.  Thrust of the SPS motor was taken as 20,000 pounds in all cases.  For both maneuvers, center of gravity location, pitch and yaw inertias, and thrust - C.G. lever arm data was provided, as a function of vehicle mass, by Reference 7.

Initial SPS thrust mistrim data was taken from the data and equations in Reference 1. Values used in this analysis are:

LOI, 3σ mistrim = 1.21° in pitch and yaw

TEI, 3σ mistrim = 1.73° in pitch and yaw

These values of mistrim include the contributions of the thrust vector control system error sources and the center of mass uncertainty. In order to isolate their effects, initial thrust mistrim and C.G. motion are the only two error sources which were included in the simulations. Ideal guidance system alignment and operation is assumed in all cases.

3. RESULTS

To isolate and evaluate the effects due to C.G. motion, cases for 0° initial mistrim conditions were simulated for each maneuver. The 0° initial mistrim curves of Figures 1 through 4 are plots of the difference in pitch and yaw plane velocity between the DAP and the unity DAP simulations. This is equivalent to the difference between nominal and ideal vehicle performance. The 3σ initial mistrim curves are plots of the velocity difference between the 3σ and unity DAP cases.

Previous DAP/vehicle analyses (Reference 8) showed that for the CSM/LM vehicle the velocity effects due to C.G. motion are greater in the pitch than yaw plane. This is further confirmed by comparing the 0° initial mistrim curves of Figures 1 and 2. These curves, which give the difference between nominal and ideal cross-axis velocity as a function of burn time, show that the C.G. motion effects produce maxima of 3 fps in the yaw plane and 3.8 fps in the pitch plane for the LOI maneuver. The thrust misalignment corrector loop in the DAP and the cross-product steering law produce C.G. motion effect corrections which drive the error velocity to zero at the end of the burn in the characteristic cross-product steering fashion. Reference 8 also proved that the effects of ±3σ initial thrust mistrim are symmetrical about the 0° mistrim curve. Because of this, only +3σ curves are presented here. Referring to Figure 1, +3σ values of initial mistrim produce maxima of 8 and 10 fps respectively in the pitch plane. These values quickly and smoothly approach those due to C.G. motion alone and produce no residual velocity error effects at thrust termination.

In the yaw plane, ±3σ initial mistrim produces maxima of 11 and 10 fps respectively (Figure 2), the curve shapes being very comparable to the pitch case.

Data on the TEI maneuver (Figures 3 and 4), shows that the C.G. motion effects (0° initial mistrim curves) are 2.5 fps and 3.5 fps maximum in pitch and yaw respectively and that the characteristic cross-product steering effect is also very apparent in the curve shapes. Initial mistrim of $\pm 3\sigma$ produced maxima of 9 fps in both planes which then were very well controlled and eliminated by cut-off time.

SUMMARY AND CONCLUSIONS

For either the LOI and TEI maneuver C.G. motion produces cross-axis velocity error maximum of 3.8 fps or less. All C.G. motion effects are smoothly and completely corrected for by the end of the burn. The DAP thrust misalignment corrector loop and the cross-product steering law produce a very satisfactory control system when evaluated with the cross-axis error velocity criteria.

For $+3\sigma$ values of initial mistrim, transient cross-axis velocity deviations of up to 11 fps occur, however, the system, as synthesized, had no difficulty in controlling this effect and producing the characteristic cross-product steering smooth curve reaching essentially zero at thrust termination.

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Attachments
  Appendix
  Figures 1, 2, 3 & 4
  References

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## APPENDIX

### Trajectory and Vehicle Parameters

#### A. Trajectory Data - Inertial Selenocentric Coordinates

|  |  | LOI | TEI |
|---|---|---|---|
| Initial Position(ft) | X | 4675554. | 745609. |
|  | Y | 4007883. | 5655407. |
|  | Z | 1775855. | 2392799 |
| Initial Velocity(fps) | $\dot{X}$ | 4237.7721 | 5239.6414 |
|  | $\dot{Y}$ | -5575.0024 | -437.90385 |
|  | $\dot{Z}$ | -4234.2529 | -595.10425 |
| Nominal End of Burn Position(ft) | X | 5860571. | 1588126. |
|  | Y | 1995187. | 5545135. |
|  | Z | 505647. | 2267285. |
| Nominal End of Burn Velocity(fps) | $\dot{X}$ | 1719.4316 | 7706.4261 |
|  | $\dot{Y}$ | -4499.9447 | -1254.0516 |
|  | $\dot{Z}$ | -2173.3359 | -1330.0475 |
| Time of Burn(Sec) |  | 382.106 | 119.067 |

#### B. Vehicle Parameters

|  | LOI | TEI |
|---|---|---|
| Thrust(lbs) | 20,000. | 20,000. |
| Mass (slugs) Initial | 2786.9603 | 1024.3970 |
| End of Burn | 2032.6797 | 789.3580 |

APPENDIX (Continued)

| | | |
|---|---|---|
| GLC (cross product steering equation curvature constant) | 1. | .5 |
| Kl (cross product equation gain) | .075 | .1 |
| Filter gain (Initial) | .0082 | 4.12263 |
| Decrement | .000081 | .1364737 |
| $3\sigma$ Initial Thrust Mistrim(deg) | 1.21° | 1.73° |

Time-to-Go Algorithm (from Reference 5)

$$TGO = \frac{-\overline{VG}\cdot\overline{1}_{\Delta VG}}{\left|\frac{\Delta\overline{VG}}{\Delta T}\right|}\left[1 + \frac{\overline{VG}\cdot\overline{1}_{\Delta VG}}{2VE}\right] - TDECAY$$

Where $\overline{VG}$ and $\overline{1}_{\Delta VG}$ are the velocity to be gained and its direction of change in one guidance cycle. $\Delta T$ is the guidance system cycle time, and VE is the engine exhaust velocity. TDECAY is the thrust tail-off correction factor, zero for this analysis.

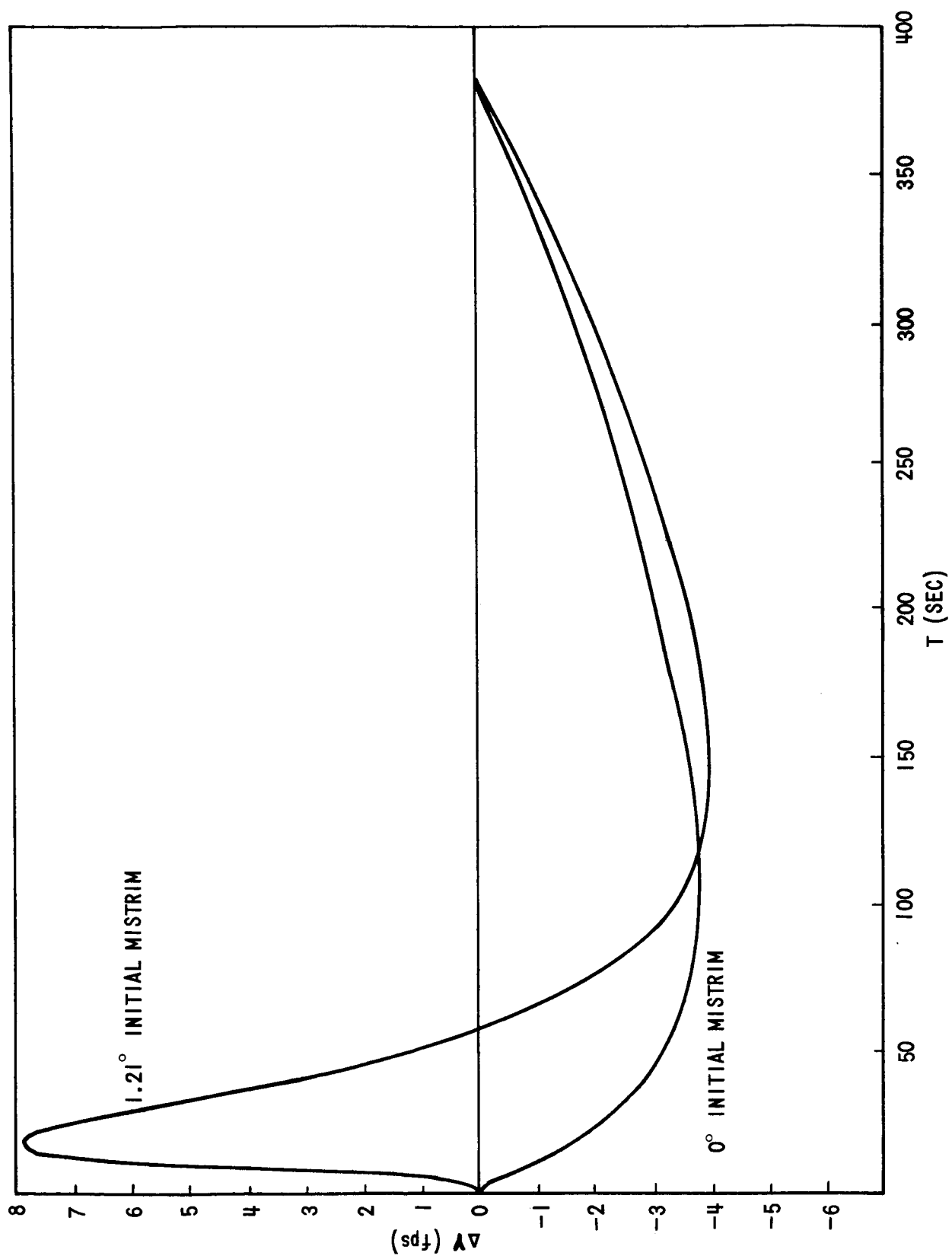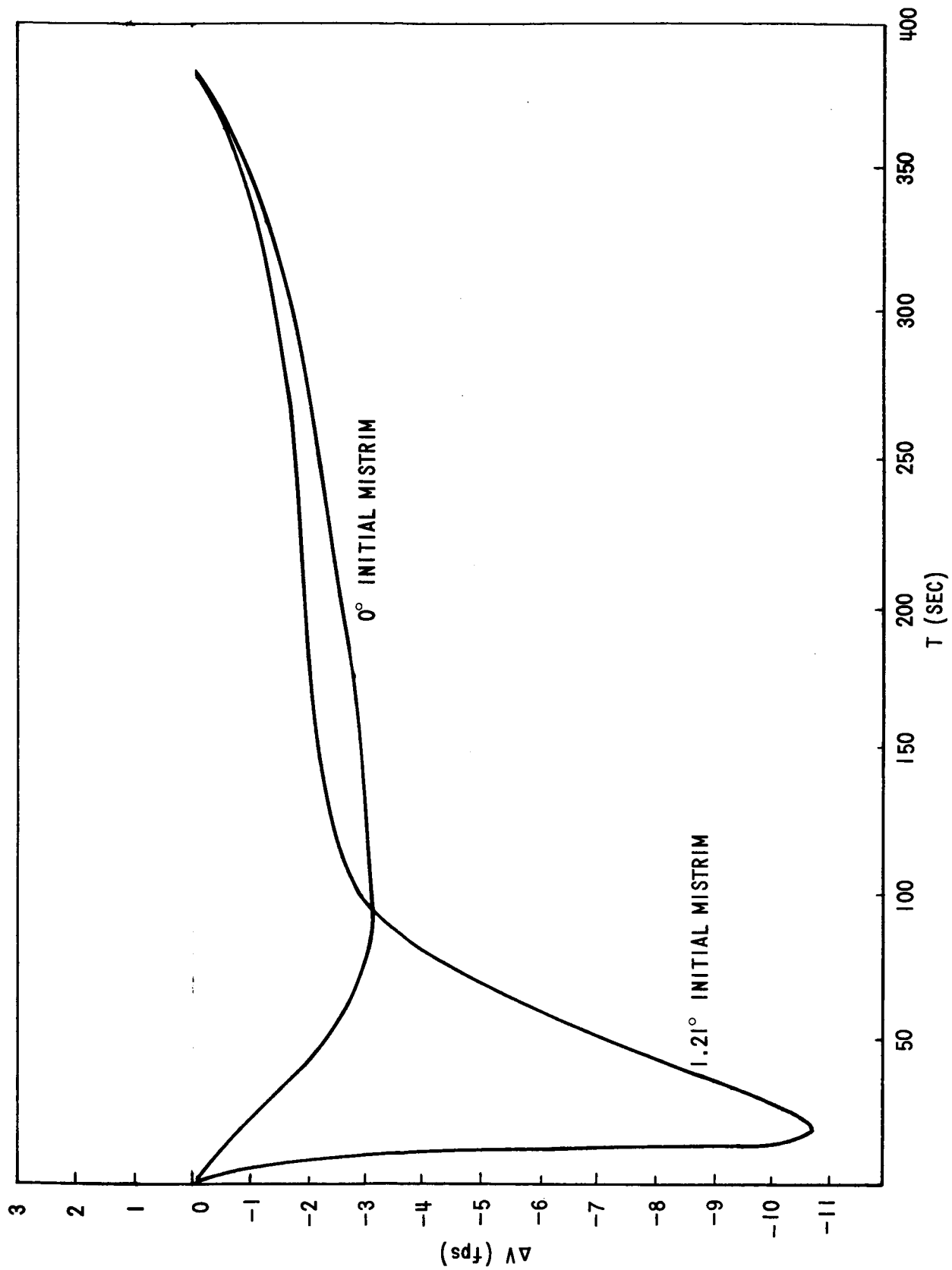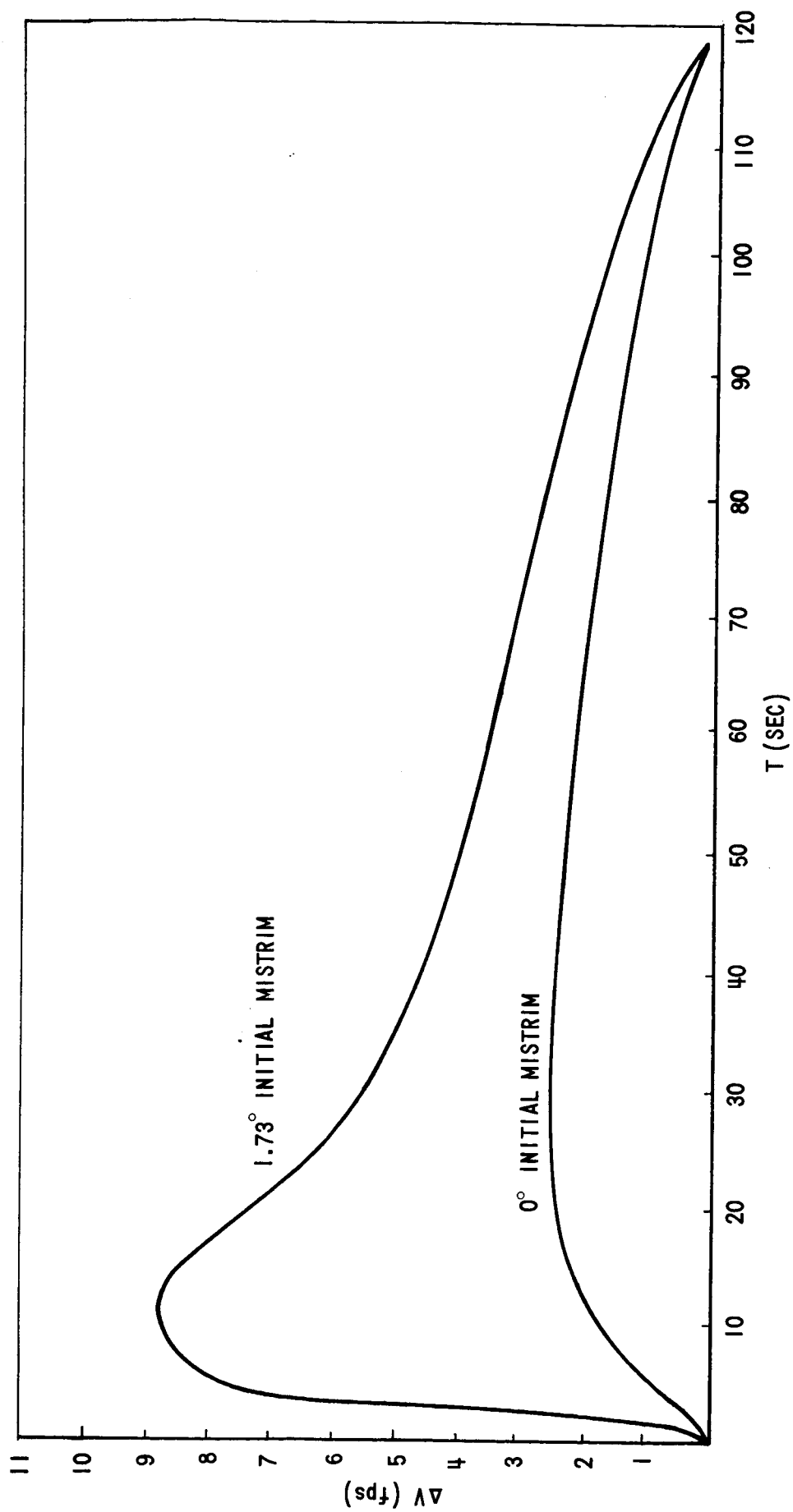FIGURE 1. LOI MANEUVER-PITCH PLANE

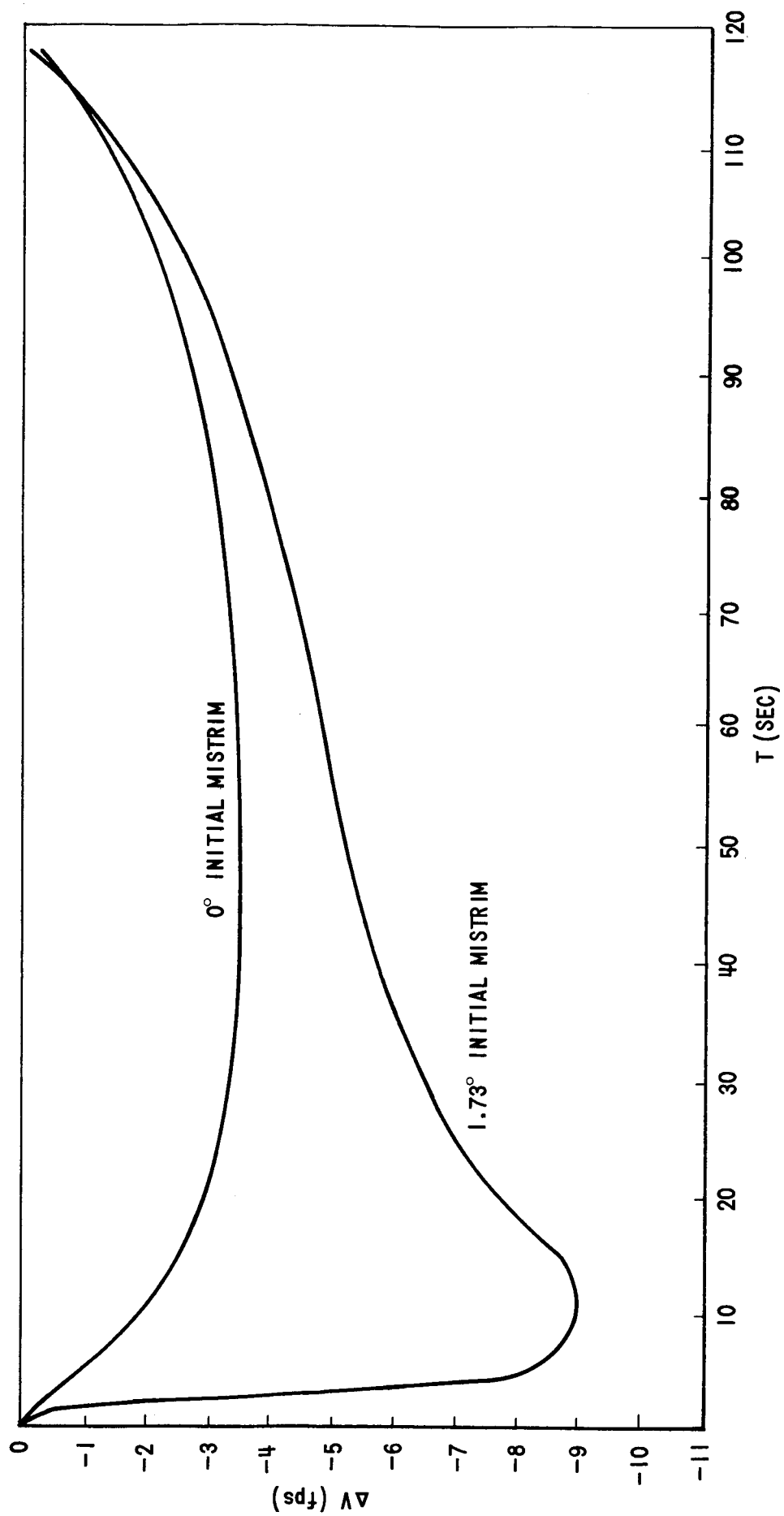FIGURE 2. LOI MANEUVER-YAW PLANE

FIGURE 3. TEI MANEUVER·PITCH PLANE

FIGURE 4. TEI MANEUVER·YAW PLANE

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3. MIT/IL, Space Guidance Analysis Memorandum #18-67, Performance of the Thrust Vector Control System for the CSM and CSM/LEM Configurations, October 13, 1967.

4. MIT/IL, AS-205 Verification Results, Program Sundisk, Volume IV, Digital Autopilot Test Results, February, 1968.

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8. Bellcomm Memorandum for File, Initial Thrust Mistrim and C.G. Motion Effects on Translunar and Transearth Midcourse Correction Maneuvers - Case 310, by F. La Piana, Department 2012, August 22, 1968.

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